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Treeline vegetation composition and change in Canada's western Subarctic from AVHRR and canopy reflectance modeling

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A B S T R A C T

Climate change is expected to have significant impacts on northern vegetation, particularly along transition zones such as the treeline. Studies of vegetation composition and change in this ecotone have largely focussed on local analysis of individual trees using labour intensive stand reconstruction techniques, which are spatially limited and do not consider vegetation types other than trees. Remote sensing may be well suited to monitoring recent changes across the treeline because it captures integrated changes of all vegetation life forms over large spatial extents. This research examines treeline vegetation composition and change along the western subarctic treeline mapped by Timoney et al. (1992) using a 1 km resolution, 22-year AVHRR archive from 1985–2006. While most remote sensing studies on vegetation change in arctic and subarctic regions only exploit information contained in the Normalized Difference Vegetation Index (NDVI), we examine long-term reflectance trends in AVHRR bands 1 and 2 in addition to NDVI. The GeoSail canopy reflectance model is used to map treeline composition by combining information from 22-year summertime and early springtime composite images. A set of spectral change vectors are then generated from GeoSail simulations and used to classify trends in AVHRR along the treeline to estimate vegetation change. Evaluation of vegetation composition against the MODIS Vegetation Continuous Fields (VCF) product that has been recently validated along the treeline reveals good spatial correspondence. Temporal trends are shown to agree with literature on tundra–taiga vegetation dynamics in recent decades. Evidence is presented that suggests replacement of bare surfaces with herb, conifer decline along the southern treeline, increased shrubiness, and increased conifer recruitment and growth in the north.

1. Introduction

The treeline is expected to change in structure and composition with continued climate warming (Grace et al., 2002). Vegetation changes along this ecotone will alter vegetation–atmosphere interactions impacting energy, biochemical cycling, and eventually climate. These changes will also have implications for people who depend on hunting wildlife, such as woodland caribou across Northern Canada.

The treeline represents a transition zone between continuous forest and tundra, sometimes referred to as 'taiga'. Although the gradient that defines the treeline is based on tree density characteristics, there are other important compositional changes that occur along the latitudinal treeline gradient as well. In general, the northern boreal–southern treeline zone is occupied by discontinuous forest with relatively high understory biomass that includes erect shrubs, tussock tundra, lichen and sedge meadows. Understory biomass becomes progressively less abundant northward, occupied at the northern limit by trees in isolated catchments, with low biomass upland tundra consisting of more sedge and prostrate shrub form and less erect shrub than at the southern limit (Payette, 1983; Timoney et al., 1992).

Analyses of temporal vegetation change along the treeline have focussed mainly on trees and have generally been investigated using stand reconstruction techniques. Stand reconstruction is a labour intensive method that involves aging trees, but allows the investigation to examine historical changes dating back to the age of the earliest tree cohort (Lescop-Sinclair & Payette, 1995; Szeicz & Macdonald, 1995). Such studies tend to be localized, though there is a growing body of literature on historical treeline dynamics in different regions of Canada that provides an extensive, but spatially coarse understanding of treeline dynamics. Satellite remote sensing has advantages for monitoring vegetation composition change along the treeline due to its ability to monitor all vegetation life forms simultaneously. However, satellite data only extends as far back as the early 1970s, providing a relatively recent treeline record.

Mapping and monitoring changes in the treeline and tundra regions present challenges that are less frequently encountered

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further south. First, significant spectral confusion exists between broadleaved vegetation mixed with water, and needle leaf canopies that form most of the treeline. Needle leaved trees generally have lower red and NIR reflectance that broadleaved vegetation, while broadleaf reflectance is suppressed by the presence of nearby standing water, leading to spectral confusion between wet environments covered by broad leaved vegetation and drier needle leaved vegetation. This confusion is a primary reason why radar is desirable to map wetlands due to its sensitivity to moisture conditions (Li & Chen, 2005). Secondly, extreme and sudden changes are minor in the taiga–tundra region, while subtle vegetation changes due primarily to the direct effects of climate change on temperature, and indirect effects on hydrology and permafrost dominate. Fire generally does not occur above Larsen's forest line (1965) (Timoney, 1995), defined as the limit where forest covers 50% of the forest surface, while land-use is minor. Therefore, change detection methods developed further south may not be optimal to detect the subtle, progressive changes to both vegetation vigour and composition due to climate warming.

To date, understanding of change in northern regions has largely been derived through trend analysis of long-term satellite NDVI and climate records (Myneni et al., 1997; Slayback et al., 2003; Zhou et al., 2003; Goetz et al., 2005; Pouliot et al., 2009). Much of the research has identified a trend of increasing NDVI in northern regions, but assessment of the "functional types" contributing to these NDVI trends has not been widely undertaken. Olthof et al. 2009, examined Landsat time series and simple numerical modeling as a means to assess potential vegetation compositional changes. Results suggested replacement of bare and lichen cover with vascular vegetation cover types consistent with in situ observations. In the current research, a methodology that incorporates a canopy reflectance model, trend detection and change vector analysis is assessed as a means to investigate change in basic vegetation types along the treeline from a 1985–2006 AVHRR data record.

1.1. Remote sensing of vegetation and change

Most national to global-scale investigations of vegetation change using satellite remote sensing imagery have relied solely on the NDVI as a proxy for gross photosynthesis (Myneni et al., 1997; Goetz et al., 2005). The $NDVI = (NIR - red)/(NIR + red)$ is calculated as the difference between red and near infrared (NIR) reflectance normalized by the sum of the two to help compensate for extraneous factors such as topography and sun-sensor geometry. At the leaf level, red reflectance is affected primarily by chlorophyll absorption, while NIR reflectance is related to volume scattering due to internal leaf structure. At the canopy level, conifer shoots absorb more light than broad leaves due to a higher recollision probability of photons within needle leaved canopies (Smolander & Stenberg, 2005). This higher recollision enhances the likelihood of light interacting multiple times with needles, and thus increases needle leaf absorption in both red and NIR wavelengths compared to broadleaved canopies. Because recollision probability is independent of wavelength (Smolander & Stenberg, 2005), both red and NIR bands are similarly affected by shadowing caused by three-dimensional canopy structure and differences between bands are mainly due to absorption and needle or leaf scattering properties. Therefore, the effect of shadowing is minimized using the NDVI, and structural information due to shadow is suppressed in addition to other unwanted factors such as topography and illumination. When the sun's position is relatively constant as is the case when monitoring inter-annual vegetation change between consecutive peak-of-season satellite image acquisitions, information on structural change can be derived from the effects of shadowing on individual spectral band reflectances (Seed & King, 2003). The inclusion of individual spectral band reflectances in addition to NDVI should therefore provide added information on vegetation structure and structural change.

1.2. Canopy reflectance modeling

Canopy reflectance modeling is similar to forward linear mixture modeling; only it has a number of advantages that apply particularly to the treeline due to vegetation structure. Canopy reflectance models linearly combine endmember fractions weighted by their reflectance values similar to forward mixture modeling, but also consider radiative transfer through canopies to derive more deterministic fractional canopy components. Along the treeline where vertical structure of trees and shrubs combines with low sun elevation angles that cast long shadows on ground vegetation, accounting for radiative transfer of different vertical layers should improve canopy reflectance estimates over forward linear mixture modeling that does not account for vertical structure.

Because canopy reflectance modeling simulates the interaction between radiation and vegetation, it is a physical modeling approach normally run in forward mode to estimate canopy reflectance of a given vegetation composition and structure. Peddle et al. (2003, 2004) simulate canopy reflectance inversion by running the model multiple times in forward mode to generate a set of structural parameters and their corresponding reflectances in a modeling approach called 'Multiple-Forward-Mode', or MFM. The lookup table that associates canopy structure and its related reflectance is then used to assign vegetation parameters based on observed reflectance, enabling the model to run in a pseudo inversion mode. This approach has been shown to be useful for forest classification in Peddle et al. (2004) and forest structural change detection in Peddle et al. (2003). In change detection, however, Peddle et al. (2003) used a post classification approach whereby each time interval was classified independently using MFM and then compared.

In the current paper, we employ a similar approach to MFM to determine vegetation composition along the treeline in Canada's western Subarctic. Since MFM uses reflectances of pure endmembers corresponding to each major vegetation type in the scene and relates the model outputs to satellite-derived surface reflectances, it relies on absolute reflectance values. These values can be difficult to obtain reliably in both field and satellite based measurements due to endmember variability and numerous corrections applied to satellite imagery to produce a nadir surface reflectance product such as BRDF and atmospheric corrections. To reduce this dependence for monitoring, we rely on relative differences in modeled canopy reflectances to produce a set of change vectors (Lambin & Strahler, 1994) and relate these to trends in AVHRR red, NIR and NDVI derived using robust trend detection methods.

Using a canopy reflectance model in forward mode, we first use a set of vegetation composition and structural attributes to produce a set of corresponding spectral signatures. By varying composition and structure in the model, we then produce a set of spectral change vectors in AVHRR band 1 (Red), band 2 (NIR) and NDVI that can be related to trends in the satellite imagery. We use 22 years of summer and early springtime AVHRR imagery from 1985 to 2006 to map treeline composition and change. The analysis is limited to the treeline region of Canada's western Subarctic mapped by Timoney et al. (1992).

2. Data and methods

2.1. Timoney's treeline

Timoney et al. (1992) mapped the treeline transition from forest to tundra using airphoto analysis and ground truth data collected in the summers from 1982 to 1984. Airphotos were traditional black and white at 1:50 000 to 1:70 000 scales taken between 1950 and 1980. A total of 1314 airphotos were analysed, covering approximately 24% of the treeline, adjacent subarctic and low arctic. Isolines joining similar ratios of tundra:treed area were generated, bounded by 1000:1 and 1:1000 treed to upland tundra cover at the southern and northern limits, respectively. A total of seven isolines were produced, with